Precision & Performance Conference 2025, Cranfield University, UK, 17th- 20th November 2025

Experimental Evaluation of Burr Formation in High and Low Speed Micromilling of Inconel 718 with Coated Carbide Tools using Statistical Methods

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Abstract
Inconel 718, a nickel-based superalloy, is renowned for its robustness under extreme conditions offering excellent resistance to heat, wear and corrosion. These attributes make it a material of choice in high-demand applications across aerospace, power generation and medical sectors. As precision engineering trends drive the need for compact and functionally critical components, micromachining has surfaced as an essential approach for fabricating fine features in such hard-to-machine alloys. The present study explores burr formation characteristics during micro-milling of Inconel 718 under both high speed and low speed cutting domains. A systematic experimental design based on the Taguchi L16 orthogonal array was implemented to examine the influence of process parameters including spindle speed, feed per tooth and depth of cut with uncoated and three different coated tools. Analysis of Variance (ANOVA) was employed to quantify the influence of each input variable on burr morphology specifically burr width. The results demonstrate that elevated spindle speeds significantly reduce burr size, yielding finer edge finishes compared to lower speed operations. Cutting speed emerged as the dominant factor at low-speed machining contributing 32.88% to burr width variance while tool type accounted for 27.87% at high-speed machining domain. nACo and uncoated tools outperformed in suppressing burr formation in low and high-speed machining domains, respectively. These outcomes underscore the potential of high-speed micro-milling combined with optimized parameter selection and tool coating to enhance edge quality, offering a viable path toward precision manufacturing of superalloy components with minimal post-processing.

High speed micro-milling; Burr formation; Burr width; Inconel 718 superalloy; Analysis of Variance

1. Introduction

The escalating demand for miniaturized components across advanced industrial domains has catalyzed significant progress in micromachining technology. This demand is particularly evident in aerospace, defense, biomedical and Micro-Electromechanical Systems (MEMS) applications where lighter compact and multifunctional parts are essential [1]. Micromachining has gained prominence for its ability to fabricate intricate three-dimensional geometries with high precision across diverse materials [2]. Micromilling, a miniaturized variant of conventional milling, differs fundamentally due to the microscale tool–workpiece interaction, where cutting responses are strongly influenced by tool edge radius and minimum chip thickness [3]. The complexity further intensifies when machining advanced alloys like Inconel 718.

Inconel 718 is extensively employed in demanding environments including gas turbines, aerospace propulsion systems and nuclear reactors due to its exceptional combination of high mechanical strength, thermal stability and corrosion resistance [4,5]. However, these advantageous properties also render it highly challenging to machine. Its inherent toughness and poor thermal conductivity lead to significant heat accumulation in the cutting zone, promoting rapid tool degradation. The complexity further increases in micromachining where cutting mechanics differ from conventional processes. Optimizing cutting strategies and tool materials is therefore essential in micromilling. The application of advanced tool coatings plays a pivotal role in micromilling where the cutting-edge radius closely matches the uncut chip thickness. Studies show that coated micro-tools extend tool life and improve surface quality when processing Inconel 718 [6,7].

Burr formation is a critical challenge in micro-machining because it compromises precision of the manufactured components. Although burr manifest in both macro- and micro-scale machining, the approaches for managing it differ considerably. Burrs in macro-machining, owing to their comparatively larger dimensions, are addressed through various conventional deburring techniques. In contrast, micro-scale burrs become more complex to eliminate because of stringent precision requirements [8]. Post-process deburring is discouraged and burr suppression is achieved through process optimization particularly by adjusting machining parameters and tool geometry [9,10]. Burr generation during micro-end milling is governed by complex material deformation mechanisms and is strongly affected by parameters such as cutting speed, feed per tooth, depth of cut and tool types. Since the scale of burrs is comparable to that of the machined features, focused research on burr evolution in aerospace alloys like Inconel 718 bears considerable relevance [11].

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This research undertook a comparative analysis of burr formation during high- and low-speed micromilling of Inconel 718 using coated and uncoated micro-tools. A systematic experimental framework coupled with statistical evaluation through ANOVA was implemented to comprehensively investigate the influence of machining parameters. The outcomes provide practical insights for optimizing micromilling of hard-to-machine alloys, contributing to the advancement of precision manufacturing for critical engineering applications.

2. Experimentation Section

2.1. Materials and Methods

The Inconel 718 specimen with dimensions of 10 mm × 10 mm × 50 mm was securely fixed in a vice and its top surface was prepared using a 12 mm two-flute end mill to establish a reference plane for subsequent micromilling operations. No separate residual-stress characterization was performed in the present study because the focus was on relative burr-formation trends under controlled, identical starting conditions. All specimens were taken from the same Inconel 718 batch to ensure uniform microstructure; metallographic analysis was omitted as the study focused solely on burr-formation trends under consistent material conditions. The machining trials were performed on a YDPM MV-1060 three-axis vertical milling center, configured for slot milling with a cutting length of 10 mm and a spacing of 3 mm between adjacent slots. All trials employed a single straight slotting strategy to maintain consistency and minimizing tool-path variability. All micromilling trials were performed dry at ambient temperature to eliminate coolant-induced variability. The machine was integrated with an ultra-precision high-speed spindle (HES810-BT40), capable of operating up to 125 m/min. The experimental configuration, including tool–workpiece alignment, is illustrated in Figure 1.

(a) (b)

Figure 1. Experimental setup: (a) vertical milling center; (b) Machining process

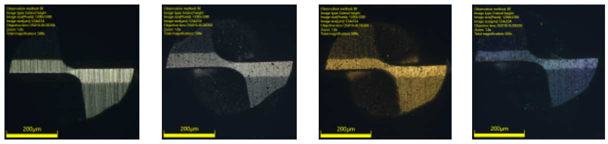
2.2. Cutting Tool Specifications

In micromilling of Inconel 718, evaluating tool materials is essential due to the combined influence of tool geometry, operating conditions and material properties. This nickel-based superalloy characterized by its abrasive microstructure and exceptional thermal resistance imposes significant mechanical and thermal stresses [12]. To overcome these challenges, advanced coatings such as TiAlN (titanium aluminum nitride), TiSiN (titanium silicon nitride), and nACo (AlTiSi-based nanocomposite) have been widely adopted for both high- and low-speed micromilling operations. The specifications of these coatings provided by Changzhou North Carbide Tool Co,.Ltdare shown in Table 1 [13].

Table 1. Specifications of coatings

Specification	nACo	TiSiN	TiAlN
Color	Blue	Golden	Black
Hardness (HV)	4500	3600	3200
Oxidation temperature (◦C)	1200	1000	900
Coefficient of Friction	0.4	0.45	0.3

The application of these coatings improves the tool hardness, thermal endurance and wear resistance allowing the cutting edge to retain sharpness. The experiments utilized two-flute tungsten carbide end mills, each with a diameter of 500 µm (0.5 mm) and a helix angle of 30°. Coatings were deposited with an average layer thickness of 3 µm [13]. The cutting-edge radius for TiAlN, TiSiN, nACo coated and uncoated tools and observed average values of 2.57 µm, 3.04 µm, 2.92 µm and 2.43 µm, respectively. No measurable variation was observed among the tools used. Figure 2 presents the micro-end mills employed in this study.



(a) (b) (c) (d)

Figure 2. Tools: (a) Uncoated; (b) TiAlN; (c) TiSiN; (d) nACo

2.3. Design of Experiments

To systematically investigate the effect of process parameters on burr formation during micromilling, statistical methodologies such as Design of Experiments (DoE) and Analysis of Variance (ANOVA) are commonly employed [14]. In this study, the Taguchi L16 orthogonal array was adopted, providing an efficient scheme for evaluating multiple variables with a limited number of trials. Table 2 consolidates the machining parameters and their four levels, distinguishing between high- and low-speed domains designed separately. Feed rate, depth of cut and tool coating levels were maintained constant across both speed domains. To eliminate the influence of progressive tool wear, a new tool was used for each trial, giving a total of 64 runs. Parameter ranges and coating specifications were selected from prior studies [13,15]. ANOVA was subsequently applied to quantify the relative contribution of each parameter, highlighting the dominant factors influencing burr formation.

Table 2. Levels of input parameters for both domains

Input Parameters	Level 1	Level 2	Level 3	Level 4
High Speed Domain (m/min)	50	75	100	125
Low Speed Domain (m/min)	6	7.5	9	10.5
Feed (µm/tooth)	0.5	1.5	2.5	3.5
Depth of Cut (µm)	60	90	120	150
Tool Coatings	Uncoa	TiAlN	TiSiN	nACo

3. Measurement of Responses

During micro-milling, distinct burr types including top burrs, exit burrs, entrance burrs and bottom burrs are produced as a function of the cutting direction and the interaction dynamics between the tool and workpiece. The top burr, which remains attached to the upper surface of the workpiece, is measured as the horizontal projection from the slot wall [9]. Observations indicate that burr formation is more pronounced on the down-milling side, which can be attributed to the relatively lower cutting-edge velocity, a phenomenon consistent with the findings reported by Syed H Imran Jaffery [16].

Table 3. Burr Width at Low Speed

Test	Input Parameters				Burr
	High Speed	Feed	DoC	Tool Coating	Width (µm)
1	6	0.5	60	UCoat	196.88
2	6	1.5	90	TiAlN	181.95
3	6	2.5	120	TiSiN	275.82
4	6	3.5	150	nACo	252.59

5	7.5	0.5	90	TiSiN	245.86
6	7.5	1.5	60	nACo	218.29
7	7.5	2.5	150	UCoat	424.17
8	7.5	3.5	120	TiAlN	292.35
9	9	0.5	120	nACo	284.46
10	9	1.5	150	TiSiN	261.62
11	9	2.5	60	TiAlN	254.17
12	9	3.5	90	UCoat	359.43
13	10.5	0.5	150	TiAlN	272.09
14	10.5	1.5	120	UCoat	196.64
15	10.5	2.5	90	nACo	132.77
16	10.5	3.5	60	TiSiN	227.55

In the present investigation, the maximum top burr width for each slot on the down-milling side was measured using a digital microscope DXS-1000, OLYMPUS, Tokyo, Japan. The microscope was automatically calibrated. It features a telecentric optical design with motorized 10X zoom, offering total magnification up to 9637X. Measurement accuracy and repeatability in the X–Y plane were ±3% and 2%, respectively. Burr width was measured at multiple magnifications between 100X and 1000X to ensure precise edge definition. The corresponding response values under varying machining conditions are summarized in Table 3 and Table 4 for the low- and high-speed domains, respectively.

Table 4. Burr Width at High Speed

Test	Input Parameters				Burr Width (μm)
	High Speed	Feed	DoC	Tool Coating	
1	50	0.5	60	UCoat	123.35
2	50	1.5	90	TiAlN	157.56
3	50	2.5	120	TiSiN	198.16
4	50	3.5	150	nACo	127.56
5	75	0.5	90	TiSiN	151.42
6	75	1.5	60	nACo	141.61
7	75	2.5	150	UCoat	196.67
8	75	3.5	120	TiAlN	168.01
9	100	0.5	120	nACo	203.09
10	100	1.5	150	TiSiN	221.01
11	100	2.5	60	TiAlN	249.69
12	100	3.5	90	UCoat	99.28
13	125	0.5	150	TiAlN	169.41
14	125	1.5	120	UCoat	137.25
15	125	2.5	90	nACo	108.25
16	125	3.5	60	TiSiN	161.03

4. Results and Discussions

To maintain methodological rigor and mitigate the impact of tool degradation, each experimental scenario was replicated with a new cutting tool under identical conditions. The collected responses were analyzed using ANOVA, applying the "lower-the-better" quality characteristic approach to determine factor significance and relative contribution. A threshold of statistical significance was defined at the 95% confidence level, considering parameters with p-values below 0.05 as critical contributors to burr formation [17].

Table 5. ANOVA at Low Speed

Source	DF	Seq SS	Contribution	F-Value	P-Value
Speed	3	47250	32.88%	13.44	0.000
Feed	3	21757	15.14%	6.19	0.004
DoC	3	31143	21.67%	8.86	0.001
Coatings	3	21270	14.80%	6.05	0.005
Error	19	22268	15.50%		
Total	31	143689	100.00%		

The statistical contributions of the process variables are presented in Table 5 and Table 6 for the high- and low-speed micromilling domains, respectively. Analysis revealed that, under low-speed conditions, cutting speed was the dominant factor, accounting for 32.88% of the variance in burr formation. In contrast, under high-speed conditions, tool coating exhibited the highest effect with a 27.87% contribution.

Table 6. ANOVA at High Speed

Source	DF	Seq SS	Contribution	F-Value	P-Value
Speed	3	11263.5	21.54%	18.64	0.000
Feed	3	9719.2	18.59%	16.09	0.000
DoC	3	12903.7	24.68%	21.36	0.000
Coatings	3	14570.7	27.87%	24.12	0.000
Error	19	3826.0	7.32%		
Total	31	52283.1	100.00%		

Micro-milling of Inconel 718 often leads to substantial burr formation owing to its high plastic deformability and difficulties in chip fracture which deteriorate dimensional precision. Burr generation is significantly influenced by the interplay of cutting parameters and tool geometry [18]. Menghua Zhou et al. examined spindle speed, feed, depth of cut and tool overhang for burr morphology concluding that these exhibited a linear dependence with burr size [19]. The main effect plots depicting burr width relative to speed, feed, depth of cut and tool coatings are presented in Figure 3.

Micromilling at elevated spindle speeds substantially reduces burr formation by decreasing chip load and suppressing built-up edge accumulation. Elevated spindle speeds enhance process stability and facilitate smoother material removal which yield reduced burrs as illustrated in Figure 3(a). The experimental evidence confirms that increasing rotational speed enhances chip evacuation efficiency which minimizes burr width, whereas lower speeds intensify burr growth [20]. A consistent pattern was observed across both speed domains that the burrs initially increased at lower speeds and then declined reaching its minimum value at 10.5 and 125 m/min [15]. Cutting speed controls heat generation in the primary shear zone, affecting material softening and shear behavior. Consequently, higher speeds promote thermal softening and smoother chip flow, leading to fewer burrs.

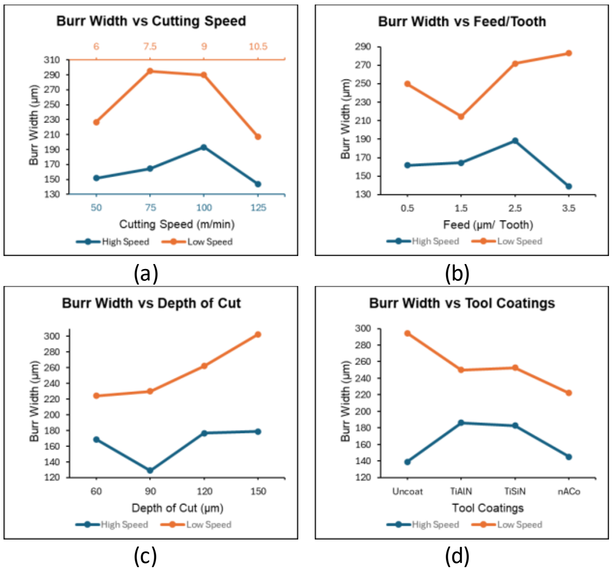


Figure 3. Main effect plots for Burr Width: (a) Cutting Speed; (b) Feed; (c) Depth of Cut (d) Tool Coatings

A nonlinear relationship between burr width and feed rate was identified across both low- and high-speed machining conditions. At low domain, burr width was initially high, decreased at intermediate feed, and increased again at higher levels as can be seen in Figure 3(b). Conversely, in high-speed micromilling, width first rose with increasing feed rate but decreased within the range of 2.5–3.5 µm/tooth, attaining its minimum at 3.5 µm/tooth. This behaviour is linked to a transition in the dominant removal mechanism where lower feeds intensify ploughing-induced plastic deformation [15].

The depth of cut exhibited a moderate yet notable influence on burr generation. An escalation in cutting depth consistently leads to a rise in burr width across both speed domains as depicted in Figure 3(c). This behaviour is attributable to the growth of uncut chip thickness as deeper engagement extends chip length. Additionally, greater penetration depths elevate thermal loads which intensify plastic flow and influence burr morphology [13]. Khan M. A. et al. corroborate this trend by linking burr width growth to the increased uncut chip thickness associated with higher depths of cut [21].

The influence of tool coatings in the high-speed machining domain was observed to be twice as significant compared to the low-speed domain, contributing 27.87% and 14.80%, respectively. At low domain, nACo-coated tools minimized burr formation whereas uncoated tools generated the largest widths. Conversely, in the high-speed domain, uncoated tools demonstrated superior performance by producing the smallest burr widths as represented in Figure 3(d) while TiAlN-coated tools were associated with larger sizes.

4.1. Confirmatory Runs

Validation experiments were carried out to verify the accuracy of the ANOVA-based predictions under both best and worst machining conditions. The outcomes together with the corresponding parameter settings are detailed in Table 7.

Table 7. Optimal combination of input parameters

Conditions		Input Parameters				Response
		Speed *Vc*	Feed *fz*	DoC *ap*	Tool Coating	Burr Width
Low Speed	Best	10.5	1.5	60	nACo	181.37
	Worst	7.5	3.5	150	Uncoat	427.71
High Speed	Best	125	3.5	90	Uncoat	91.26
	Worst	100	2.5	150	TiAlN	261.03

5. Conclusions

This experimental work was undertaken successfully to bridge the identified research gap by exploring multiple parameter settings combined with different tool coating strategies during the micromilling of Inconel 718 across high- and low-speed domains. The influence of each input variable on burr formation was elucidated through statistical analysis using ANOVA. The findings below not only support optimization of process variables but also strengthen the reproducibility and predictive reliability of micromachining outcomes.

- Burr formation is consistently more pronounced within the low-speed machining domains whereas substantially reduced burr widths are recorded under high-speed cutting conditions across all examined input variables. This comparative distinction clearly demonstrates the effectiveness of high-speed micromilling in mitigating burr formation and improving overall machining quality.
- Under low-speed machining conditions, cutting speed emerged as the dominant variable, accounting for a contribution of 32.88%. Within the high-speed machining domain, tool coating exhibited the greatest influence on performance with a relative impact of 27.87%.
- nACo-coated tools exhibited the minimal burr width under low-speed domain while uncoated tools demonstrated comparatively better results in high-speed machining domain.

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